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Development of Optimization Tool for Air-Conditioning System Operation

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Abstract

This study aims to realize the optimization of the air-conditioning system operation. Although set values of air-conditioning systems are usually fixed, variable setting values are used in this study. It is possible that less energy consumption with greater comfort is achieved by selecting appropriate set values in consideration of situations which change from day to day. In this study, the optimization of air-conditioning system operation is carried out by selecting appropriate set values in terms of energy consumptions and the comfort.

The prediction of building heat loads is necessary to realize the optimization in ever-changing environments. Therefore, a more robust optimization method which handles errors in the prediction was proposed, and the optimization tool for an air-conditioning system was developed. The developed optimization tool is incorporated into the Building and Energy Management System (BEMS), and it automatically changes setting values acquiring data including driving data from the BEMS. Experiments were conducted to clarify the effectiveness of the tool, and simulations in the case of a medium-scale office building were also done for the evaluation of the tool.

Experiments prove that the evaluation value tends to improve by using the optimization tool. As the result of simulations, it is found out that the evaluation value improves by considering prediction errors and that the evaluation value is reduced by 12.1% at maximum.

1. INTRODUCTION

In the operation phase of a building, the indoor heat generation changes drastically depending on the building usage or the number of machines in rooms. The deterioration in air-conditioning system components also occurs. However, it is rare that setting values of a system are changed according to situations. In many cases, the system operation is continued with inappropriate setting values. The optimization of the air-conditioning system operation aims at realizing "an appropriate operation of an air-conditioning system" by changing setting values according to situations that change every day. The prediction of building heat loads is required to calculate optimal setting values, however, it is subject to errors. Calculations by the data with errors might cause adverse results. Therefore, a more robust optimization method to handle errors in the prediction was proposed, and the optimization tool of an air-conditioning system was developed. The developed optimization tool is incorporated in the Building and Energy Management System (BEMS), and it automatically changes setting values by acquiring the data including driving date from the BEMS. In this report, the effectiveness of the optimization tool is clarified by experiments, and its effect in a medium-scale office building is also examined by simulations.

2. OPTIMIZATION TOOL

2.1 Concept of the tool

Figure 1 shows the concept of the developed optimization tool. It consists of two parts: the part for predicting weather conditions and the internal heat generation and the part for optimizing calculations. The weather conditions and the internal heat generation are predicted using measured data in the past.

Outside air temperature and the absolute air humidity are predicted by the Auto-regressive Integrated Moving Average

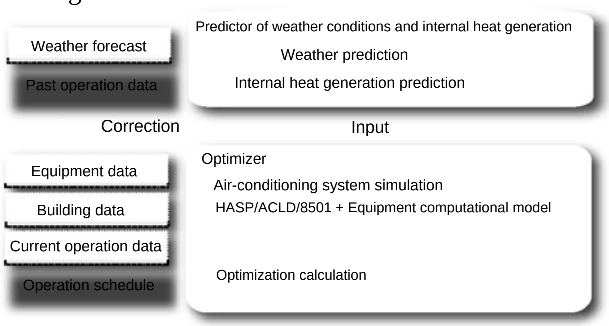

Figure 1. The Conceptual Diagram of the Developed Optimization Tool

(ARIMA) model [1],[2]. The solar radiation on a horizontal surface and the amount of cloud are predicted by a statistical method [3] using the weather forecast.

The internal heat generation is estimated by using operation data in the past, and the value is used as predicted value of the internal heat generation. All these predicted values are used as inputs to the thermal load simulation program, and set values including supply air temperature and chilled water temperature are determined by the air-conditioning system simulation program which utilizes the optimization method.

HASP/ACLD/8501 [4] (HASP) is used for the calculation of thermal loads, and the air-conditioning system simulation program is constructed by component models that are mostly taken from HASP/ACSS/8502 [5] or HVACSIM+ [6].

2.2 Optimization method which considers errors in the thermal load prediction

Figure 2 shows the schematic diagram of the relationship between loads and energy consumptions.

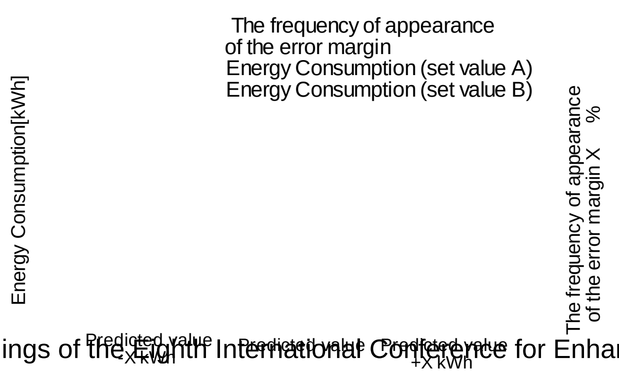

Figure 2. The Schematic Diagram of the Relationship between Loads and Energy Consumptions

Since many optimization techniques assumes that there is no margin of error in the thermal load prediction, the best set value is selected based on the predicted value which lies in the center of this figure. In the example of this figure, the set value B is selected, because selecting the set value B results in slightly smaller energy consumption compared to selecting the set value A. However, when an actual load becomes predicted value plus X kWh, selecting the set value B wastes more energy than the case of selecting the set value A. It is likely that optimization techniques select the set value A which has better stability as the set value if errors are taking into account.

As a method of selecting the appropriate set value even in such a case, calculations not only at the exact predicted value of thermal load but also at the predict value plus X kWh and at the predict value minus X kWh are proposed. Set values can be evaluated by taking weighted average of calculation results (energy consumption and so on) according to the frequency of appearance of the error margin X.

3 EXAMINATION OF THE EFFECTIVENESS OF THE OPTIMIZATION TOOL BY EXPERIMENTS

3.1 The HVAC&R experimental analysis system

The HVAC&R experimental analysis system in Kyushu University was used for experiments. This System is composed of an air source heat pump chiller, a primary pump, an air handling unit and the secondary pump. Picture1, Figure3, Figure4, Figure 5 and Table 1 show the appearance of the HVAC&R Experimental Analysis System, the ground plan, the sectional plan, the system diagram of the air-conditioning system and specifications of the building, respectively. ON/OFF control is carried out at the chiller. VWV 2-way valve is under the PI control, and it adjusts the air supply temperature to the set temperature.

VAV unit is also operated under PI control, and it changes the airflow volume by moving a dumper so that the room temperature is adjusted to the set temperature. The minimum amount of the air flow in each VAV unit is 100 m^3/h.Frequencies of the inverters of the pump and fans change according to the flowing volume, the water pressure and the air volume.

Picture 1. The Appearance of the HVAC&R Experimental Analysis System

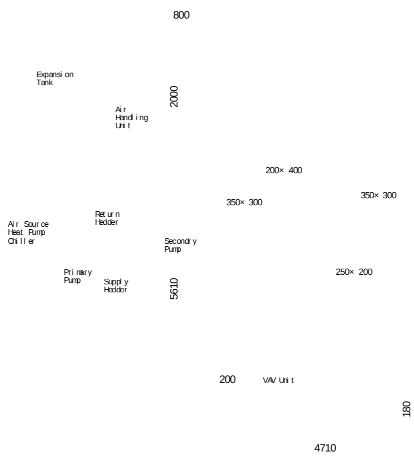

Figure 3. The Ground Plan of the HVAC&R Experimental Analysis System

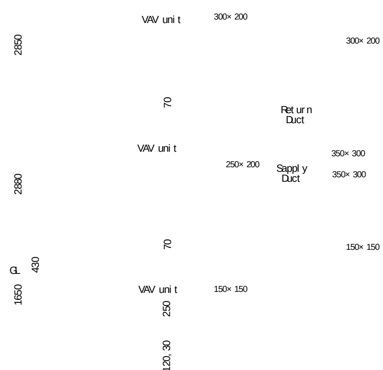

Figure 4. The Sectional Plan of the HVAC&R Experimental Analysis System

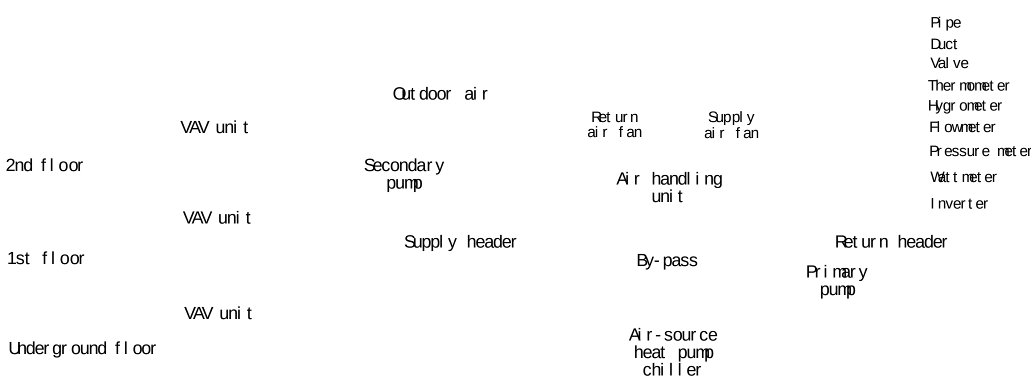

Figure 5. The System Diagram of the HVAC&R Experimental Analysis System

Table 1. Specifications of the Building of HVAC&R Experimental Analysis System

Location	The Chikushi campus of Kyushu University (Kasuga City)
Building area	$35.84m^2$
Total floors space	$107.53m^2$ (air-conditioning area: $27.13m^2 \times 3$ rooms = $81.39m^2$)
Number of stories	2 stories above the ground and 1 story under the ground
Height	Eave height: 6.15m, 1st floor height: 2.7m
Structure	Box frame type reinforced concrete panel construction

3.2 Methodology of experiments

Experiments were performed twice in summer and winter. The experiment period in summer was from July 27 to August 1, 2007 and from August 19 to 27, 2007. The experiment period in winter was from December 14, 2007 to January 3, 2008. An air-conditioning system was used for cooling in summer and for heating in winter. Table 2 shows the operation settings for each day. The optimized operation with the optimization tool was performed for six days in the summer term and for eight days in the winter term, and the normal operation was performed on the rest of days. The air-conditioning system was operated for 12 hours from 9 o'clock to 21 o'clock including holidays.

Table 2. The Operation Settings for Each Day

(a) Summer Experiment

July					August									
27	28	29	30	31	1	19	20	21	22	23	24	25	26	27
Fri	Sat	Sun	Mon	Tue	Wed	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon
Normal Operation			Optimized Operation			Normal Operation			Optimized Operation			Normal Operation		

(b) Winter Experiment

December												January		
14	15	16	22	23	24	25	27	28	29	30	31	1	2	3
Fri	Sat	Sun	Sat	Sun	Mon	Tue	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu
Normal Operation				Optimized Operation			Normal Operation			Optimized Operation				

The optimization tool predicts the weather condition and the internal heat generation at 8 AM based on the weather forecast data announced by the Japan Meteorological Agency at 5:00AM on the same day and the measured data until 8:00AM. The calculation for the optimization is executed based on results of this prediction, and the best set values are applied as set values on that day. The following three set values are optimized: the supply air temperature, the outlet chilled water temperature of chillers and the discharge pressure of the secondary pump. The best combination of these three values is searched by the best-subset selection procedure among all combinations shown in Table 3. Set values at the normal operation are also underlined in Table 3.

Table 3. Options of the Set Values

Set Values	Options	
the supply air temperature	Summer	15/16/17/18/19/20/21/22[°C] (59/60.8/62.6/64.4/66.2/68/69.8/71.6[F])
	Winter	24/26/28/30/32/34/36/38[°C] (75.2/78.8/82.4/86/89.6/93.2/96.8/100.4[F])
the outlet chilled water temperature of chillers	Summer	5/6/7/8/9/10/11/12/13/14/15[°C] (41/42.8/44.6/46.4/48.2/50/51.8/53.6/55.4/57.2/59[F])
	Winter	Celsius : 35/37/39/41/43/45/47/49/51/53/55[°C] (95/98.6/102.2/105.8/109.4/113/116.6/120.2/123.8/127.4/131[F])
the discharge water pressure of the secondary pump	Summer Winter	40/60/80/100/120/140/160[kPa] (0.408/0.612/0.816/1.02/1.22/1.43/1.63[kgf/cm^2])

* Set values at the normal operation are underlined

The system operation is evaluated by means of the evaluation function given in Equation 1 and Equation 2. The evaluation function is constituted of the electric power consumption and the penalty value which is determined by the control condition of the room temperature. Therefore, the smaller the evaluation value is, the better the operation. W in

Equation 1 is a parameter that decides the balance between the power consumption and the penalty value. W is fixed at 0.01 by a prior examination. C in Equation 2 is a coefficient which converts the difference between the set room temperature and the actual room temperature into the penalty value, and the value of C varies depending on seasons, namely summer, winter and spring /autumn. The room humidity is not included in the evaluation function in this examination, though it is necessary to consider it as well as the room temperature in order to ensure the comfort.

$$V = E_{ac} + W \times P_R \qquad \text{(Equation 1)}$$

$$P_R = C(D_B + D_1 + D_2)/3 \qquad \text{(Equation 2)}$$

Where

V = Evaluation Value[kWh]

Eac = Electric(al) power consumption of the day [kWh]

W = Weighted Parameter for the penalty value [-]

PR = The penalty value based on the control condition of the room temperature [-]

C =Conversion coefficient between room condition and the penalty value[kWh/(K h)]

D = Integration Value of absolute value of deflection from room temperature to the preset value [K h] (The affixing character shows the floor.)

3.3 Experimental results

The results of summer experiment are shown in Figure 6, Figure 7 and Figure 8, and those of the winter experiment are shown in Figure 9, Figure10 and Figure 11. In the summer experiment, the evaluation values on days with the optimized operation are smaller except August 23. It is likely that the poor evaluation value on August 23 was obtained since the weather forecast (rain) was totally different from the actual weather (cloudy, fine later).

From Figure 7, it is shown that the evaluation value tends to improve when the average outside air temperature of the air-conditioning hours is higher, through the correlation between the two factors is not so strong. Moreover, from Figure 9, the same tendency is found between the evaluation value and the average outside air temperature in winter.

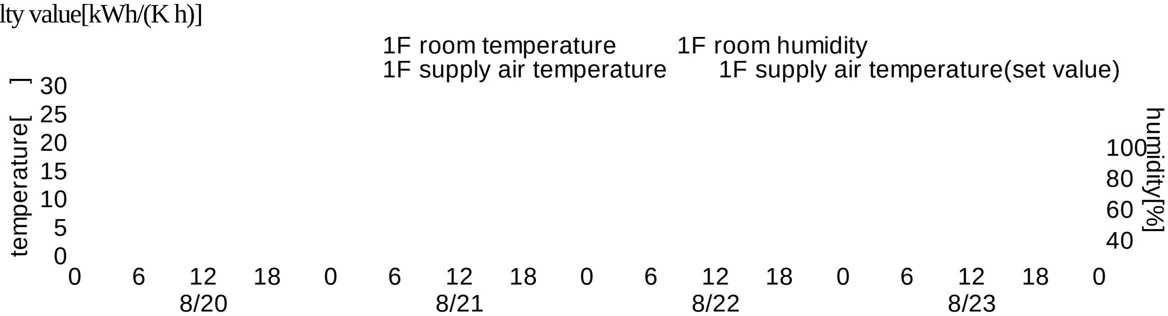

Figure 6. Room Temperature, Room Humidity and Supply Air Temperature in Summer Experiment

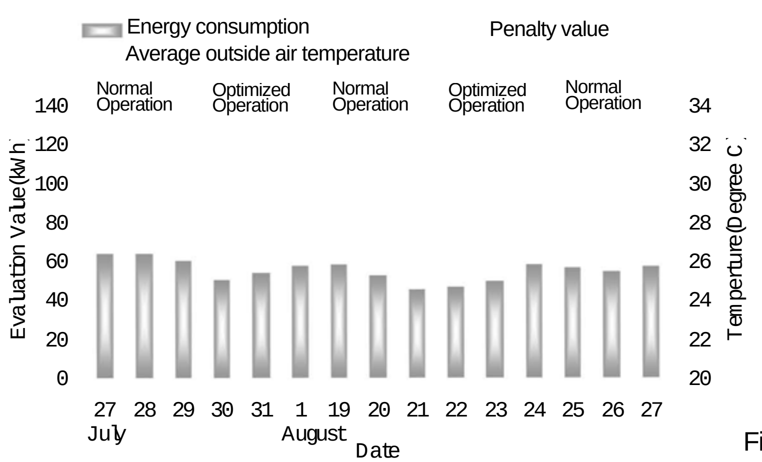

Figure 7. Evaluation Value in Summer Experiment

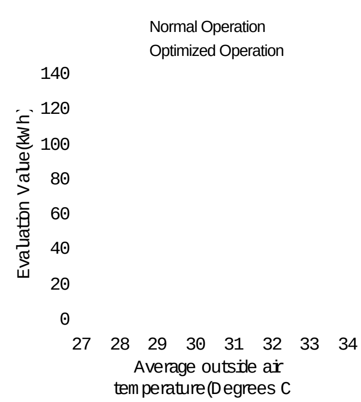

Figure 8. Relationship between the Evaluation Value and the Average Outside Air Temperature in Summer Experiment

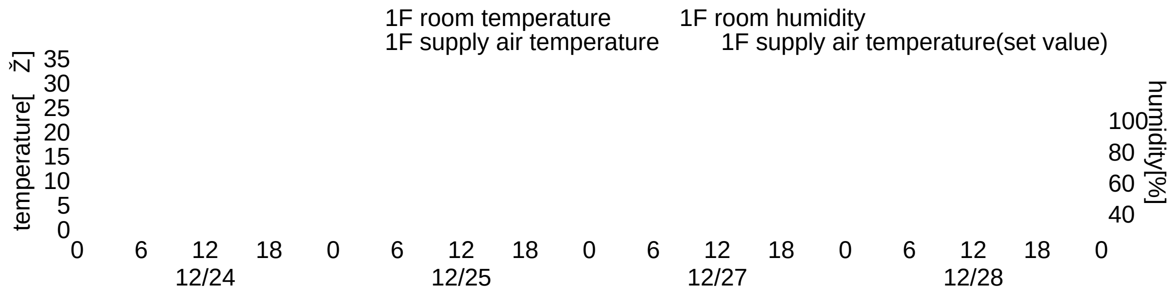

Figure 9. Room Temperature, Room Humidity and Supply Air Temperature in Winter Experiment

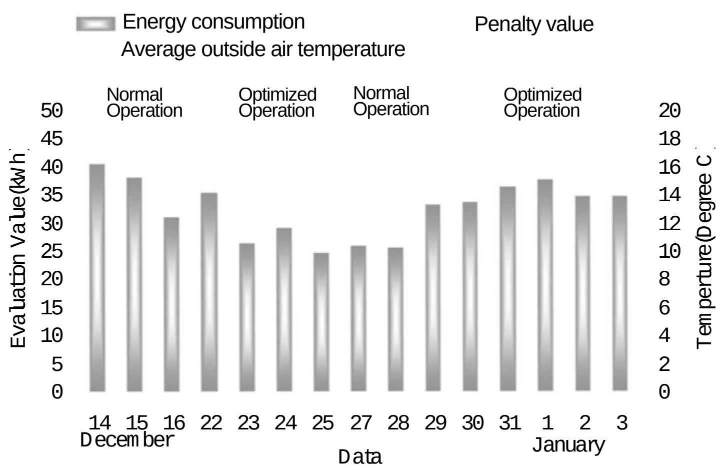

Figure 10. Evaluation Value in Winter Experiment

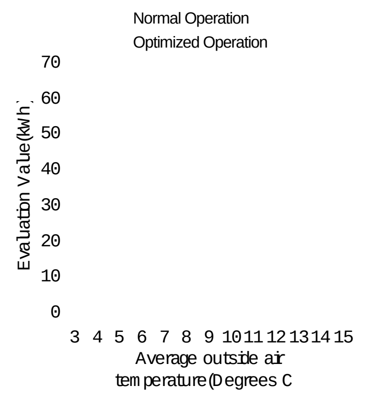

Figure 11. Relationship between the Evaluation Value and the Average Outside Air Temperature in Winter Experiment

4. APPLICATION OF THE OPTIMIZATION TOOL TO AN AIR-CONDITIONING SYSTEM IN A MEDIUM-SCALE OFFICE BUILDING

4.1 Descriptions of the building and the air-conditioning system

The effectiveness of the optimization tool was also examined by using the air-conditioning system simulation. The simulation model was established for a medium-scale office building, and its description is given below.

The building has a total floor space of about 30,000m^2. Further descriptions of the building are given in Table 4. Figure 12 is a schematic diagram of the HVAC&R system. The water thermal storage tank in this building is shown in Figure 13. The thermal storage tank stores chilled-water throughout the year to meet year-round cooling loads due to the internal heat generation in computer rooms. The flow rate of the water sent to the chillers is adjusted by the PI control of two-way valves installed in pipes between the thermal storage tank and chillers, and the inlet temperature at each chiller is made equal to the set value. In the same way, outlet water temperatures of heat exchangers are kept at set values. The number of chillers operated is determined by comparing the actual thermal storage with the target value of thermal storage which is derived from set values of thermal storage at five different hours of a day.

In winter, maximum three chillers, not including the R-3 chiller, are operated depending on heating loads. The air source chiller (R-1) is used for the exhaust heat recovery by storing chilled water in the thermal storage tank.

Each room has air handling units and fan coil units. Outside air is supplied to the air handling units through another air handling unit with a humidifier which is designed to treat outside air. In winter it humidifies outside air up to the set value of dew point temperature. The amount of dehumidification is not adjusted.

Table 4. Specifications of the Object Building

Location	Oita Prefecture
Building area	6,561m^2
Total floors space	29,939m^2
Number of stories	11 stories above the ground and 2 story under the ground
Structure	CFT; Concrete Filled Steel Tube

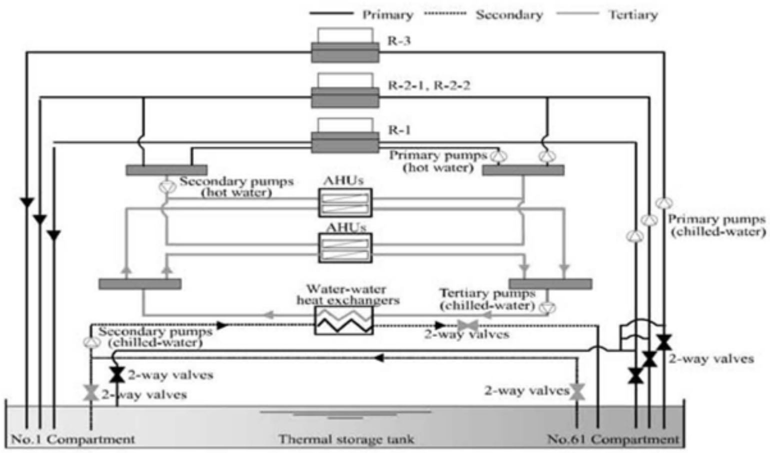

Figure 12 A Schematic Diagram of the HVAC&R system

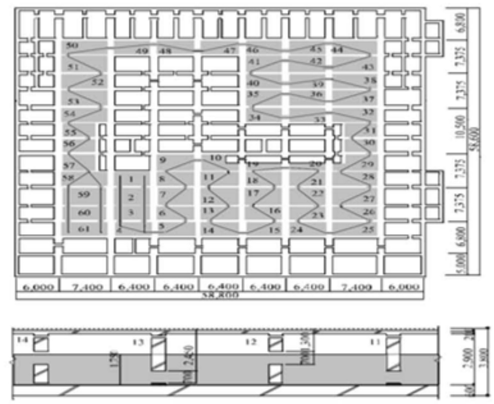

Figure 13. The Water Thermal Storage Tank

4.2 Method of the calculation and examined case

The calculation is conducted every one minute. The air conditioning system is operated from 8 o'clock to 18 o'clock on weekdays only, except computer rooms where the system is operated 24 hours everyday including weekends. Calculations are done for February, August, and October in 1995. The air-conditioning system is used for both heating and cooling in February, and only for cooling in August and October. Set room temperatures are 22 ^{o}C (71.6F) in February, 26 ^{o}C (78.8F) in August, and 24 ^{o}C (75.2F) in October. Table 5 shows combinations of set values, and the best combination which achieves the smallest evaluation value is searched among them by using the genetic algorithm [7]. The examined case is as follows.

Table 5. Options of the Set Values

Set Values		Options
the supply air temperature of Air Handling Unit for outside air	All year round	15/16/17/18/19/20/21[^{o}C] (59/60.8/62.6/64.4/66.2/68/69.8[F])
the supply air dew point temperature of Air Handling Unit for outside air	Heating term only	9/12/15/18/21[^{o}C] (48.2/53.6/59/64.4/69.8 [F])
Inlet water temperature of chillers (cooling)	All year round	11/12/13/14/15[^{o}C] (51.8/53.6/55.4/57.2/59[F])
Outlet water temperature of chillers (heating)	Heating term only	42/43/44/45/46[^{o}C] (107.6/109.4/111.2/113/114.8[F])
Tertiary outlet water temperature of Water-Water Heat Exchangers	All year round	9/10/11/12/13[^{o}C] (48.2/50/51.8/53.6/55.4[F])
Secondary inlet water temperature of Water-Water Heat exchangers	All year round	8/9/10/11/12[^{o}C] (46.4/48.2/50/51.8/53.6[F])
Ratio of thermal storage (8 o'clock)[-]	All year round	0.40/0.55/0.70/0.85/1.00
Ratio of thermal storage (13 o'clock)[-]	All year round	0.00/0.15/0.30/0.45/0.60
Ratio of thermal storage (16 o'clock)[-]	All year round	0.00/0.15/0.30/0.45/0.60
Ratio of thermal storage (18 o'clock)[-]	All year round	0.00/0.15/0.30/0.45/0.60
Ratio of thermal storage (22 o'clock)[-]	All year round	0.00/0.15/0.30/0.45/0.60

Case A Normal operation. The normal set values for each month are shown in Table 6.

Case B Set values are decided according to the actual load and no errors in the load prediction is assumed.

Case C Set values are decided according to the thermal load simulation which utilizes the weather forecast data. Although the prediction of the indoor heat generation is necessary for the optimizing calculation, the actual value is used for the calculation.

Case D Though the calculation method of Case D is similar to that of Case C, errors in thermal load prediction is considered in Case D. From the distribution of errors in the past two weeks, the evaluation value is determined using the weighted average.

Table 6. The Normal Set Values

Set Values	February	August	October
the supply air temperature of Air Handling Unit for outside air	20°C (71.6F)	18°C (64.4F)	
the supply air dew point temperature of Air Handling Unit for outside air	15°C (59F)	-	
Inlet water temperature of chillers (cooling)	45°C (113F)	-	
Outlet water temperature of chillers (heating)	12°C (53.6F)		
Tertiary outlet water temperature of Water-Water Heat Exchangers	10°C (50F)		
Secondary inlet water temperature of Water-Water Heat exchangers	9°C (48.2F)		
Ratio of thermal storage (8 o'clock)[-]	1.0		
Ratio of thermal storage (13 o'clock)[-]	0.7		
Ratio of thermal storage (16 o'clock)[-]	0.4		
Ratio of thermal storage (18 o'clock)[-]	0.2		
Ratio of thermal storage (22 o'clock)[-]	0.3		

4.3 Calculation results

Figure 14 shows the comparison of evaluation values for each case. Case B achieves the highest reduction rate of the evaluation value, since the actual load is used for the calculation. However, this case cannot happen in reality because errors occur without fail in the prediction. The reduction in evaluation values is seen in all three months, and the reduction rate of Case D to Case A is 11.2% in February, 12.1% in August and 5.1% in October. The reduction rate of Case D to Case C is -0.1% in February, 1.9% in August and 1.3% in October. This shows that better optimization is achieved except in winter by considering errors in the thermal load prediction. It is possible that the performance of the optimization tool in Case D is poorer than it should be, since the margin of error becomes small as a result of inputting the true value of the indoor heat generation instead of a predicted value. Therefore, it will be necessary to execute simulations including the prediction of the indoor heat generation in the future.

5. CONCLUSIONS

In this report, the effectiveness of the optimization tool for air-conditioning system operation was examined by experiments and simulations. The results of experiments showed that the optimization tool tended to improve the evaluation value. From simulations of an air-conditioning system in a medium-scale office building, it was clarified that operation with the optimization tool, which took errors into account, improved the evaluation value compared with normal operation, and maximum 12.1% of reduction in the evaluation value was achieved.

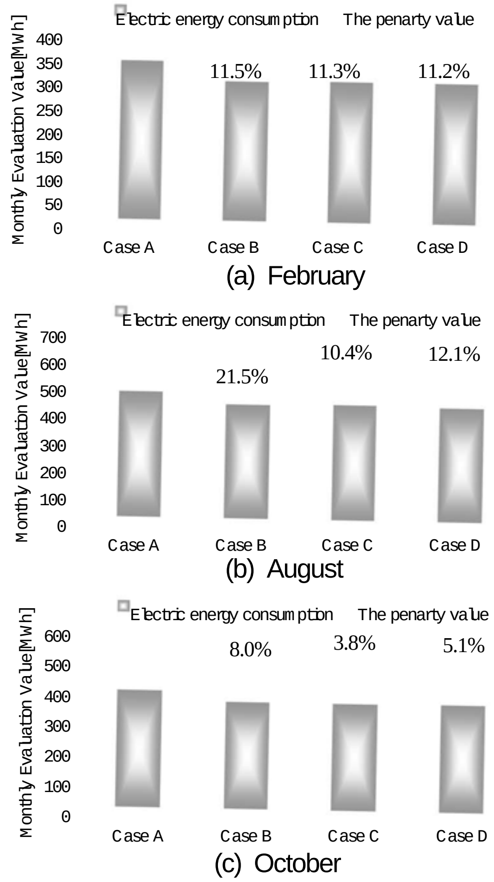

Figure 14. The Comparison of Evaluation Values for Each Case (Simulation Result)

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